PATENT

Docket No. ***D-349***

Commissioner of Patents and Trademarks
Washington, D.C. 20231

NEW APPLICATION TRANSMITTAL

Transmitted herewith for filing is the patent application of

Inventor(s): Gee L. Lui and Kuang Tsai

For (title): Gaussian Minimum Shift Keying (GMSK) Precoding Communication Method

1. Type of Application

This new application is an **ORIGINAL** application.

2. Benefit of Prior U.S. Application(s) (35 USC 120) - None

CERTIFICATION UNDER 37 CFR 1.10

I hereby certify that this New Application Transmittal and the documents referred to as enclosed therein are being deposited with the United States Postal Service on this date September 7 1999 *in an envelope as "Express Mail Post Office to Addressee" Mailing Label Number* EJ380377485US *addressed to the: Commissioner of Patents and Trademarks, Washington, D.C. 20231*

Carole A. Mulchinski
(Type or print name of person mailing paper)

Carole A. Mulchinski
(Signature of person mailing paper)

3. Papers Enclosed Which Are Required for Filing Date Under 37 CFR 1.53(b) (Regular) or 37 CFR 1.153 (Design) Application

__23__ Pages of specification
__7__ Pages of claims
__1__ Pages of Abstract
__2__ Sheets of drawing

/__/ informal

/__/ in triplicate

4. Additional papers enclosed

/__/ Preliminary Amendment

/X_/ Information Disclosure Statement

/X_/ Form PTO-1449

/X_/ Small Entity Statement

5. Declaration or oath executed by INVENTOR(S)

/X_/ Enclosed

6. Inventorship Statement

The inventorship for all the claims in this application is THE SAME.

7. Language: ENGLISH

8. Assignment

/X_/ An assignment of the invention to __The Aerospace Corporation__ __P. O. Box 92957 (M1/040), Los Angeles, CA 90009-2957__

/X_/ is attached

/__/ will follow

9. Certified Copy

Certified copy(ies) of application(s) __X__ are not applicable ____ are attached ____ will follow.

10. *Fee Calculation*

/X/ **Regular application**

CLAIMS AS FILED						
Number Filed			**Number Extra**		**Rate**	**Basic Fee** **$760.00**
Total Claims	**-**	**-20=**	**0**	**X**	**$ 18.00**	
Independent Claims	**-**	**-3=**	**1**	**X**	**$ 39.00**	**00.00**
Multiple dependent claim(s), if any					**$260.00**	

/__/ **Amendment cancelling extra claims enclosed**

/__/ **Amendment deleting multiple dependencies enclosed**

/__/ **Fee for extra claims is not being paid at this time**

Filing Fee Calculation **$760.00**

11. *Small Entity Statement(s)*

/X/ Verified Statement(s) that this is a filing by a small entity under 37 CFR 1.9 and 1.27 is(are) attached.

$380.00

12. *Fee Payment Being Made At This Time*

/__/ No filing fee is to be paid at this time. (This and the surcharge required by 37 CFR 1.16(e) can be paid subsequently.)

/X/ Enclosed

/X/ Basic filing fee $ 380.00

/X/ Recording assignment ($40.00; 37 CFR 1.21(h)(1)) $ 40.00

Total fees enclosed $ 420.00

13. ***Method of Payment of Fees***

/X/ charge Account No. 01-0428 in the amount of $ 420.00. A duplicate of this transmittal is attached.

14. ***Authorization to Charge Additional Fees***

/X/ The Commissioner is hereby authorized to charge the following additional fees by this paper and during the entire pendency of this application to Account No. 01-0428.

/X/ 37 CFR 1.16 (filing fees)

/X/ 37 CFR 1.16 (presentation of extra claims)

/X/ 37 CFR 1.16(e) (surcharge for filing the basic filing fee and/or declaration on a date later than the filing date of the application)

/X/ 37 CFR 1.17 (application processing fees)

/X/ 37 CFR 1.18 (issue fee at or before mailing of Notice of Allowance, pursuant to 37 CFR 1.311(b).

15. ***Instructions As To Overpayment***

/X/ credit Account No. 01-0428.

Reg. No.: 32,096

Derrick Michael Reid

Signature of Attorney

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Derrick Michael Reid

Type or print name of attorney

THE AEROSPACE CORPORATION
P.O. Box 92957 (M1/040)
Los Angeles, CA 90009-2957

/X/ This transmittal ends with this page.

Attorney's Docket No. D-349

Applicant or Patentee: Gee L. Lui, Kuang Tsai

Serial or Patent No.: ______

Filed or Issued: ______

For: GAUSSIAN MINIMUM SHIFT KEYING (GMSK) PRECODING COMMUNICATION METHOD

VERIFIED STATEMENT (DECLARATION) CLAIMING SMALL ENTITY STATUS (37 CFR 1.9(f) and 1.27(d))--NONPROFIT ORGANIZATION

I hereby declare that I am an official empowered to act on behalf of the nonprofit organization identified below:

NAME OF ORGANIZATION The Aerospace Corporation

ADDRESS OF ORGANIZATION P. O. Box 92957 (M1/040)

Los Angeles, CA 90009-2957

TYPE OF ORGANIZATION

/X/ TAX EXEMPT UNDER INTERNAL REVENUE SERVICE CODE (26 USC 501 (a) and 501 (c) (3)

I hereby declare that the nonprofit organization identified above qualifies as a nonprofit organization as defined in 37 CFR 1.9(e) for purposes of paying reduced fees under Section 41(a) and (b) of Title 35, United States Code with regard to the invention entitled GAUSSIAN MINIMUM SHIFT KEYING (GMSK) PRECODING COMMUNICATION METHOD

by inventor(s) Gee L. Lui, Kuang Tsai

described in

/X/ the specification filed herewith

/ / application serial No. ______, filed ______.

I hereby declare that rights under contract or law have been conveyed to and remain with the nonprofit organization with regard to the above identified invention.

If the rights held by the nonprofit organization are not exclusive, each individual, concern or organization having rights to the invention is listed and no rights to the invention are held by any person, other than the inventor, who could not qualify as a small business concern under 37 CFR 1.9(d) or by any concern which would not qualify as a small business concern under 37 CFR 1.9(d) or a nonprofit organization under 37 CFR 1.9(e).

I acknowledge the duty to file, in this application or patent, notification of any charge in status resulting in loss of entitlement to small entity status prior to paying, or at the time of paying, the earliest of the issue fee or any maintenance fee due after the date on which status as a small entity is no longer appropriate. (37 CFR 1.28(b))

I hereby declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the United States Code, and that such willful false statements may jeopardize the validity of the application, any patent issuing thereon, or any patent to which this verified statement is directed.

NAME OF PERSON SIGNING Robert Donald Matthews

TITLE IN ORGANIZATION Assistant General Counsel

ADDRESS OF PERSON SIGNING The Aerospace Corporation

P. O. Box 92957 (M1/040), Los Angeles, CA 90009-2957

SIGNATURE Robert Donald Matthews DATE Sept. 7, 1999

09/390,395

Attorney's Docket No. D-349

Applicant or Patentee: Gee L. Lui, Kuang Tsai

Serial or Patent No.: ______

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P. O. Box 92957 (M1/040), Los Angeles, CA 90009-2957

SIGNATURE Robert Donald Matthews DATE Sept. 7, 1999

PATENT APPLICATION

Docket No.: D349

Inventor(s): Gee L. Lui, Kuang Tsai

Title: Gaussian Minimum Shift Keying (GMSK) Precoding Communication Method

SPECIFICATION

Statement of Government Interest

The invention was made with Government support under contract No. F04701-93-C-0094 by the Department of the Air Force. The Government has certain rights in the invention.

Field of the Invention

The invention relates to the field of continuous phase modulation communications. More particularly, the present invention relates to a Gaussian minimum shift keying communication method for communicating a precoded digital data stream for improved performance.

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Background of the Invention

Digital communication systems transmit data by various carrier modulation techniques. The spectrum of a digital signal can be controlled and made compact by envelope filtering or phase domain filtering. Envelope filtering filters the baseband data stream prior to upconversion to the carrier frequency and power amplification. Envelope filtering for controlling out of band power of the transmitted signal, can be found in many operational communication systems. However, the power amplifier in the transmitter must be linearized or backed off to prevent spectral regrowth of the filtered signal. The more efficient phase domain filtering approach controls the signal spectrum by frequency modulating the filtered signal onto a carrier frequency to form a continuous phase modulated (CPM) signal. The CPM signal has a constant envelope so that the power amplifier can be operated at maximum output power without affecting the spectrum of the filtered signal.

Gaussian minimum shift keying (GMSK) is a form of continuous phase modulation having compact spectral occupancy by choosing a suitable bandwidth time product (BT) parameter in a Gaussian filter. The constant envelope makes GMSK compatible with nonlinear power amplifier operation without the concomitant spectral regrowth associated with non-constant envelope signals. These attributes render GMSK an attractive modulation scheme in all high throughput frequency division multiple access satellite communication systems

where only a limited system bandwidth is available with the transmitters operating at maximum power output efficiency.

Data bits are formatted, for example, by non-return to zero (NRZ) formatting prior to Gaussian filtering, carrier modulation and power amplification. The formatted data is transmitted within data symbols of an M-ary alphabet of M possible data symbols. An M-ary GMSK signal is defined by the complex envelope described in terms of symbol energy E, symbol period T, carrier phase θ_c and phase pulse g(t) using a modulation index h and the equally probable NRZ data symbols belong to an M-ary alphabet. The GMSK phase pulse g(t) originates from a frequency response f(t) of the Gaussian smoothing filter with a single-sided 3dB bandwidth B, time truncated to a time interval of LT, where L is an integer. For Gaussian filters with small BT products, the memory length L is approximately an integer greater than or equal to 1/BT. The length L is the number of elapsed symbol periods for the GMSK signal to accrue a full phase change due to a single input symbol and hence represents the memory of the GMSK signal. A GMSK signal with memory L greater than one is termed a partial response GMSK signal. The GMSK signal is communicated to a GMSK receiver subject to interference and additive white Gaussian noise (AWGN).

An optimum GMSK receiver for an additive white Gaussian noise channel demodulates the received signal by coherent demodulation into estimated output data stream using a local carrier reference. The receiver demodulates by filtering the received signal using a bank of Laurent filters that filter the demodulated received signal

into a symbol sequence. A Viterbi decoder searches the symbol sequence for the most probable transmitted data sequence as an estimate of the original NRZ formatted data stream. A typical coherent receiver for 2-ary GMSK signal is based on a pulse amplitude modulation (PAM) representation of 2-ary CPM signals using Laurent matched filters matched to the amplitude modulated pulses in the PAM representation, and further employs the Viterbi algorithm to optimally demodulate the symbol sequence. For 2-ary GMSK transmitters with BT=1/4 and with a channel Bit Error Rate (BER) of 0.01, or more, a GMSK receiver consisting of only two matched Laurent filters and a 4-state Viterbi algorithm can nearly achieve the performance of coherent binary phase shift Keying (BPSK) signaling communications. Amplitude modulated pulses have also been extended to PAM representation for 4-ary CPM signals.

In demodulating 2-ary and 4-ary GMSK signals using the Viterbi algorithm, a differential decoder is necessary to resolve data bit ambiguities while providing a degraded BER with respect to the absolute phase demodulation. It is desirable to reduce the BER. For noisy channels, the differential decoder yields poor bit error rate performance. The Viterbi algorithm typically employs a sliding window in the demodulation process where the width of the sliding window represents the demodulation memory or delay. The surviving state sequence $U_n=(S_n,S_{n-1},\ldots,S_{n-w})$ produced by the sliding window Viterbi algorithm at any stage n depends on all the demodulated symbols $\{d_k;\ 0 \le k \le n\}$ prior to that stage, where $S_k=d_0+d_1+\ldots+d_k$. The term W is the size of the sliding window that is dictated by the memory length L of the underlying GMSK signal.

This intrinsic data dependency of the survivor state sequences U_n disadvantageously requires a differential decoder operation in the receiver when deciding on the actual demodulated symbol from successive survivors of the Viterbi algorithm resulting in a differential bit error rate (BER) degradation. These disadvantages are solved or reduced by the present invention.

Summary of the Invention

An object of the invention is to improve the bit error rate (BER) of continuous phase modulation communication systems.

Another object of the invention is to provide a precoding method for continuos phase modulation communication systems.

Yet another object of the invention is to provide a precoding method for a continuous phase modulation and coherent demodulation communication system to reduce the BER while eliminating the need for differential decoders in a receiver.

Still another object of the invention is to provide a precoding method for a Gaussian minimum shift keying (GMSK) continuous phase modulation and coherent demodulation communication system to reduce the BER while eliminating the need for differential decoders in a receiver.

The present invention is directed to a data precoding algorithm implemented in a modulator of a transmitter to substantially improve the resulting BER performance of the

continuous phase modulated (CPM) receivers, such as, Gaussian minimum shift keying (GMSK) receivers without the use of differential decoders while preserving the spectral occupancy of the GMSK signals. The precoding algorithm offers performance improvement for both 2-ary and 4-ary coherently demodulated GMSK signals. The performance improvement afforded by the precoding algorithm is up to 2.5 dB for coherent demodulation of 2-ary and 4-ary GMSK signals. The precoding algorithm may be implemented using a lookup table in the modulator circuitry without altering the desired spectral occupancy of the non-precoded GMSK signals.

Precoding improves the BER performance for coherent demodulators of the 2-ary and 4-ary GMSK signals implemented using a pulse amplitude modulated signal subject to the Viterbi algorithm. The precoding algorithm encodes the source NRZ data symbols $\{d_n\}$ prior to the GMSK modulation so that the cumulative phase of the precoded symbols $\{\alpha_n\}$ is identical to the absolute phase of the source NRZ symbols at every stage of the Viterbi algorithm, that is, $\pi h(\alpha_0+\alpha_1+...+\alpha_n)=\pi hd_n$, where h denotes modulation index. In the Viterbi algorithm, this precoding process produces a set of survivor sequences $\{U_n=(S_n, S_{n-1}, ..., S_{n-w})\}$ satisfying the condition $S_k=d_k$ at every stage k, thus making the differential decoder operation unnecessary. The precoded symbols have the same statistics as the source symbols so that the transmit spectrum of the GMSK signal is preserved. The BER is reduced using the precoding method for GMSK signals with memory of L. The memory L of a GMSK signal is related to the bandwidth time product BT of the underlying Gaussian filter by L=1/BT, where B is the single-

sided 3dB filter bandwidth in hertz. Depending upon the channel bit error rate required, the precoding method will render a signal to noise ratio (SNR) improvement of up to 2.5 dB over the same modem that demodulates GMSK signals without precoding. The proposed precoding method may also be applied to other 2-ary and 4-ary CPM signals. The only change required for these cases is to modify the pulse amplitude modulation (PAM) filters of the receiver. The precoding method encodes the source symbols $\{d_n\}$ prior to the GMSK modulation so that the resulting channel symbols $\{\alpha_n\}$ will render an optimal pseudo symbol sequence requiring no differential decoding with improved bit error rates. These and other advantages will become more apparent from the following detailed description of the preferred embodiment.

Brief Description of the Drawings

Figure 1 is a block diagram of a precoded coherent Gaussian minimum shift keying (GMSK) communication system.

Figure 2 is bit error rate (BER) performance graph for precoded and non-precoded GMSK communication links using a Gaussian filter having a bandwidth time product of BT=1/3.

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Detailed Description of the Preferred Embodiment

An embodiment of the invention is described with reference to the figures using reference designations as shown in the figures. Referring to Figure 1, a baseband representation of an M-ary Gaussian minimum shift keying (GMSK) communication system is simplistically shown for convenience to have ideal symbol timing and carrier phase synchronization. The GMSK transmitter 10 comprises a data source 11, a data precoder 12, and a GMSK modulator 14. The data source 11 continuously generates M-ary NRZ data symbols d_n chosen from an M-ary alphabet set {±1, ±3, ... ±(M-1)}. These source symbols d_n are then precoded by the data precoder 12 into a precoded symbol sequence α_n that is in turn modulated by the GMSK modulator 14. The GMSK modulator 14 includes a Gaussian filter 13, a frequency modulator 15, and a frequency converter 16. The Gaussian filter 13 is defined by a bandwidth time product (BT) that may be, for example, 1/3, where B is the one sided 3dB bandwidth in hertz of the Gaussian filter 13 and T is the data symbol duration in seconds. For M-ary GMSK signals with h=1/M, both main lobe bandwidth and sidelobe amplitude decrease with a decreasing BT. The Gaussian filter 13 provides a Gaussian filter output G(t) expressed as an accumulative filter sum response of the input sequence of precoded symbols α_n.

$$G(t) = \sum_n \alpha_n \cdot f(t - nT)$$

///

The term f(t) is the well-known GMSK frequency pulse that is a function of the BT product and is essentially zero except over a time interval of duration LT, where L is an integer representing the memory of the Gaussian filter 13. The memory length L is greater than or equal to one (L≥1). The frequency modulator 15 receives and modulates the Gaussian filter output G(t) by a predetermined modulation index h that may be, for example, 1/2. In general, lowering the modulation index h while keeping the BT product constant will reduce spectral occupancy. Preferably, the modulation index is set to h=1/M. The frequency modulator 15 transforms the Gaussian filter output G(t) into a continuous phase modulated baseband GMSK signal $Z_b(t)$. The signal amplitude of $\sqrt{(2E/T)}$ is taken as one.

$$z_b(t) = \exp\left\{ j\pi h \cdot \int_{-\infty}^{t} G(\tau)d\tau \right\} = \exp\left\{ j\pi h \sum_n \alpha_n \cdot \int_{-\infty}^{t} f(\tau - nT)d\tau \right\} \equiv \exp\left\{ j\pi h \sum_n \alpha_n \cdot g(t-nT) \right\}$$

The term g(t), which is the integral of the GMSK frequency pulse f(t), is the well-known GMSK phase pulse.

The baseband GMSK signal $Z_b(t)$ is then upconverted by the converter 16 using a carrier reference 17 and then transmitted over a communication channel 18 subject to additive white Gaussian noise (AWGN) and potential interference 19. The transmitted GMSK signal, along with noise and interference, is received by a corresponding GMSK receiver 20 equipped with a frequency converter 21. The converter 21 uses a locally generated carrier reference 22 to

downconvert the received RF signal into a baseband signal $Z_r(t)$. The received baseband signal $Z_r(t)$ is then processed by a trellis demodulator 24 to provide data estimates $\hat{d}_n$ to a data sink 26. The trellis demodulator 24 includes a filter bank 28, a sampler 30, and a Viterbi decoder 32 implementing a Viterbi algorithm.

The received baseband signal $Z_r(t)$ is first filtered by the filter bank 28 that consists of F matched filters, where F is at most $Q=2^{L-1}$ for 2-ary GMSK signaling, and at most $P=3\cdot[2^{L-1}]^2$ for 4-ary GMSK signaling. The filters in the filter bank 28 are matched to the Laurent amplitude-modulated pulses of the transmitted baseband GMSK signal $Z_b(t)$, and may be implemented as a matched filter bank or an integrate-and-dump type filter bank. The filter bank 28 provides filtered signals $r_k(t)$ for $0 \le k \le F-1$, which are sampled by the sampler 30 at every symbol time instants $t_n=nT$ to produce discrete sample values $r_{k,n}$. These sample values are then processed by the Viterbi decoder 32 to provide the data estimates $\hat{d}_n$ to the data sink 26. In order to produce reliable data estimates $\hat{d}_n$, the processing of the Viterbi decoder 32 must conform to the precoding performed by the data precoder 12 on the data symbols d_n at the transmitter 10. The number of matched filters used in the filter bank 28 also affects the reliability of the data estimates $\hat{d}_n$.

For an N symbol long 2-ary data sequence $\{\alpha_n;\ 0 \le n \le N-1\}$, the baseband GMSK signal $Z_b(t)$ has a Laurent representation.

$$z_b(t) = \exp\left\{ j\pi h \cdot \sum_n \alpha_n \cdot g(t - nT) \right\} = \sum_{k=0}^{Q-1} \sum_{n=0}^{N-1} a_{k,n} \cdot h_k(t - nT)$$

The term $Q=2^{L-1}$ is the total number of 2-ary amplitude modulated pulses $\{h_k(t)\}$, and the term $\{a_{k,n}\}$ represents the pseudo-symbols relating to the 2-ary data sequence $\{\alpha_n\}$ through radix-2 digits $\{k_i\}$ for k defined by a summation over the index i with k_o equal to zero.

$$k = \sum_{i=1}^{L-1} k_i \cdot 2^{i-1}$$

$$a_{k,n} = \exp\left\{ j\pi h \cdot \left[\sum_{m=0}^{n} \alpha_m - \sum_{i=0}^{L-1} k_i \cdot \alpha_{n-i} \right] \right\}$$

Each 2-ary amplitude modulated pulse $h_k(t)$ is related to the modulation index h and signal memory L through a generalized phase pulse c(t).

$$h_k(t) = \prod_{i=0}^{L-1} c(t + iT - (1 - k_i)LT)$$

$$c(t) = \begin{cases} \sin[\pi h - \pi h g(|t|)] / \sin(\pi h), & |t| \le LT \\ 0; & |t| \ge LT \end{cases}$$

///

The amplitude modulated pulse $h_k(t)$ is time limited to the interval $[0, D_kT]$ where $D_k = \min_{0<I<L}\{L(2-k_i)-i\}$, for examples, $D_0 = L+1$, and $D_1 = L-1$. The optimal trellis demodulator 24 for an N symbol sequence $\{\alpha_n;\ 0 \le n \le N-1\}$ corrupted by additive white Gaussian noise (AWGN) is one that maximizes 2^N correlation metrics for $0 \le m \le 2^N-1$.

$$\Lambda^{(m)} = \mathrm{Re}\left[\langle z_r(t), z_m(t)\rangle\right] \equiv \mathrm{Re}\left[\int_{-\infty}^{\infty} z_r(t)\cdot z_m^{*}(t)dt\right]$$

The term $z_m(t)$ denotes the baseband signal associated with the m-th possible sequence, and the term $z_r(t)$ denotes the AWGN corrupted received baseband signal. Expanding $z_m(t)$ in Laurent representation, these correlation metrics can be expressed in terms of the pseudo symbols $a_{k,n}^{(m)}$.

$$\Lambda^{(m)} = \sum_{n=0}^{N-1} \lambda^{(m)}(n)$$

$$\lambda^{(m)}(n) \equiv \mathrm{Re}\left[\sum_{k=0}^{Q-1} r_{k,n}\cdot a_{k,n}^{(m)*}\right]$$

$$r_{k,n} \equiv \int_{-\infty}^{\infty} z_r(t)\cdot h_k(t-nT)dt = \left[z_r(t) * h_k(-t)\right]_{t=nT}$$

The term $a_{k,n}^{(m)}$ denotes the pseudo symbols associated with the m-th possible sequence. By supplying the sampled matched filter output $r_{k,n}$ to the Viterbi decoder 32, which produces an optimal

pseudo symbol sequence $\{a_{0,n};\ 0 \le n \le N-1\}$ that maximizes Λ, the best estimate of the transmit sequence $\{\alpha_n\}$ can then be found. The trellis demodulator is simplified by retaining the first F matched filters $\{h_k(t);\ 0 \le k \le F-1\}$ in the λ equation, where F is often confined to power of two due to the batch nature of the filter duration $\{D_k\}$, e.g., $D_2=D_3=L-2$, $D_4=D_5=D_6=D_7=L-3$. For the case of $F=2$, the first two 2-ary matched-filters and the corresponding λ equation are explicitly given by matched filter equations h_0 and h_1.

$$h_0(t) = \prod_{i=1}^{L} c(t-iT)$$

$$h_1(t) = h_0(t) \cdot \frac{c(t+T)}{c(t-(L-1)T)}$$

$$\lambda(n) \equiv \mathrm{Re}\left\lfloor r_{0,n} \cdot a_{0,n}^{*} + r_{1,n} \cdot a_{1,n}^{*} \right\rfloor$$

The optimal pseudo symbol sequence produced by the Viterbi decoder 32 at any stage n inevitably involves all the demodulated symbols prior to that stage.

$$a_{0,n} = J^{(\alpha_0+\alpha_1+\cdots+\alpha_n)}$$

$$a_{1,n} = J^{\alpha_n} \cdot a_{0,n-2}$$

The term $J=\exp(j\pi h)$ depends on the modulation index h, and is $J=j$ for the case of $h=1/2$. This intrinsic data dependency requires a differential decode operation when demodulating the actual data symbol α_n.

$$\alpha_n = -j \cdot a_{0,n} \cdot a_{0,n-1}^*$$

This results in a differential BER degradation comparable to that of DPSK as compared to BPSK.

The purpose of the data precoder 12 is to encode the source symbols $\{d_n\}$ prior to the GMSK modulator 13 at the transmitter so that the resulting precoded channel symbols $\{\alpha_n\}$ will render an optimal pseudo symbol sequence $\{a_{0,n}\}$ requiring no differential decoding in the receiver, thereby improving the data demodulation performance. In mathematical terms, the data precoder 12 carries out a data mapping.

$$\alpha_n = f(d_n, d_{n-1}, \cdots, d_0)$$

The data mapping must provide a resulting expression for the pseudo symbol $a_{0,n}$ involving only d_n and not $\{d_i;\ 0 \le i < n\}$. There is no known systematic routine that can be used to determine such a mapping. Through repeated trial and error, and essentially by chance, one such mapping for 2-ary GMSK signal with modulation index h=1/2 has been found.

$$\alpha_n = d_n \cdot d_{n-1} = [d_n - d_{n-1} + 1]_{\text{mod}4} \quad (\alpha_0 = d_0)$$

This data mapping preserves the transmitted spectrum of the GMSK signal because the precoded symbols $\{\alpha_n\}$ are still equally probable as the source symbols $\{d_n\}$. The data mapping can be implemented in the data precoder 12 through the first 2-ary precoder lookup table.

First 2-ary Precoder Lookup Table		
d_n	d_{n-1}	$\alpha_n=[d_n-d_{n-1}+1]_{\text{mod}4}$
−1	−1	+1
−1	+1	−1
+1	−1	−1
+1	+1	+1

The data mapping defined by the first 2-ary precoder lookup table results in an optimal pseudo symbol sequence produced by the Viterbi decoder 32.

$$a_{0,n} = J^n \cdot J^{d_n} = j^{n+1} \cdot d_n$$

$$a_{1,n} = J^{n-1} \cdot J^{d_n - d_{n-1} + d_{n-2}} = j^n \cdot d_n d_{n-1} d_{n-2}$$

With the decoding states defined as $S_n=(d_n,d_{n-1})$, a 2^2-state 2^3-branch Viterbi algorithm is sufficient for demodulating source symbols $\{d_n\}$ when two 2-ary matched-filters are used in the filter bank 28.

A second 2-ary data precoding mapping for 2-ary GMSK signal with a modulation index h=1/2 has also been found.

$$\alpha_n = (-1)^n \cdot d_n \cdot d_{n-1} = (-1)^n \cdot [d_n - d_{n-1} + 1]_{\mathrm{mod}4} \quad (\alpha_0 = d_0)$$

The second data precoding mapping also preserves the transmit spectrum of the GMSK signal, and can be implemented in the data precoder 12 through the second 2-ary precoder lookup table.

Second 2-ary Precoder Lookup Table			
d_n	d_{n-1}	$\alpha_n=[d_n-d_{n-1}+1]_{\mathrm{mod}4}$ n: even	$\alpha_n=[d_n-d_{n-1}+1]_{\mathrm{mod}4}$ n: odd
−1	−1	+1	−1
−1	+1	−1	+1
+1	−1	−1	+1
+1	+1	+1	−1

The data mapping defined by the second 2-ary precoder lookup table results in an optimal pseudo symbol sequence produced by the Viterbi decoder 32.

$$a_{0,n} = \begin{cases} j \cdot d_n; & n: \text{ even} \\ d_n; & n: \text{ odd} \end{cases}$$

$$a_{1,n} = \begin{cases} -d_n \cdot d_{n-1} \cdot d_{n-2}; & n: \text{ even} \\ -j \cdot d_n \cdot d_{n-1} \cdot d_{n-2}; & n: \text{ odd} \end{cases}$$

With the decoding states still defined as $S_n=(d_n, d_{n-1})$, a 2^2-state 2^3-branch Viterbi algorithm is again sufficient for demodulating source symbols $\{d_n\}$ when two 2-ary matched filters are used in the filter bank 28. The choice between the first and the second 2-ary data precoding mapping is arbitrary. Extensive simulations of the first and second mappings consistently yield identical demodulation performance.

Extending the 2-ary trellis demodulator to a 4-ary trellis demodulator is based on expressing every 4-ary symbol $\alpha_n \in \{\pm 1, \pm 3\}$ in terms of two 2-ary symbols $\alpha_n^{(0)}$ and $\alpha_n^{(1)}$.

$$\alpha_n = \alpha_n^{(0)} + 2\alpha_n^{(1)}$$

This 4-ary α_n expression enables any 4-ary GMSK signal to be expressed as a product of two 2-ary GMSK signals with $h^{(0)}=h$ and $h^{(1)}=2h$ as the modulation indices, respectively.

$$\exp\left[j\pi h\sum_n \alpha_n g(t-nT)\right] = \exp\left[j\pi h^{(0)}\sum_n \alpha_n^{(0)} g(t-nT)\right] \times \exp\left[j\pi h^{(1)}\sum_n \alpha_n^{(1)} g(t-nT)\right]$$

Expressing each 2-ary signal constituent into Laurent representation and combining the product, the baseband 4-ary GMSK signal, for an N symbol long 4-ary data sequence $\{\alpha_n;\ 0 \le n \le N-1\}$, takes an amplitude modulation pulse form. The signal amplitude of $\sqrt{(2E/T)}$ is taken as one.

$$z_b(t) = \exp\left\{j\pi h \cdot \sum_n \alpha_n \cdot g(t-nT)\right\} = \sum_{k=0}^{P-1}\sum_{n=0}^{N-1} b_{k,n} \cdot f_k(t-nT)$$

The term $P= 3Q^2$ is the total number of 4-ary amplitude modulated pulses $\{f_k(t)\}$, and the terms $\{b_{k,n}\}$ are the 4-ary pseudo symbols associated with the 4-ary data sequence $\{\alpha_n\}$. All the 4-ary entities can be obtained from respective 2-ary counterparts by following a systematic enumeration approach. The optimal 4-ary trellis demodulator 24 is identical to that for 2-ary GMSK with the following replacements for a λ equation and $r_{k,n}$ equation.

$$\lambda^{(m)}(n) \equiv \mathrm{Re}\left[\sum_{k=0}^{P-1} r_{k,n} \cdot b_{k,n}^{(m)*}\right]$$

$$r_{k,n} \equiv \int_{-\infty}^{\infty} z_r(t) \cdot f_k(t-nT)dt = \left[z_r(t) * f_k(-t)\right]_{t=nT}$$

The duration of the 4-ary amplitude modulated pulses $\{f_k(t)\}$ is also presented in batches, that is, $D_0=L+1$, $D_1=D_2=L$, $D_3=\ldots=D_{11}=L-1$. The 4-ary trellis demodulator is simplified by retaining the first F=1, F=3 or F=12 matched filters in the filter bank 28. For the case of F=3, the 4-ary matched filters and the corresponding λ equation and pseudo symbols can be explicitly expressed.

$$f_0(t) = h_0^{(0)}(t) \cdot h_0^{(1)}(t) \equiv h_0(t; h = h^{(0)}) \cdot h_0(t; h = h^{(1)})$$
$$f_1(t) = h_0^{(0)}(t+1) \cdot h_0^{(1)}(t) \equiv h_0(t+1; h = h^{(0)}) \cdot h_0(t; h = h^{(1)})$$
$$f_2(t) = h_0^{(0)}(t) \cdot h_0^{(1)}(t+1) \equiv h_0(t; h = h^{(0)}) \cdot h_0(t+1; h = h^{(1)})$$

$$\lambda(n) \equiv \mathrm{Re}\left[r_{0,n} \cdot b_{0,n}^* + r_{1,n} \cdot b_{1,n}^* + r_{2,n} \cdot b_{2,n}^*\right]$$

$$b_{0,n} = a_{0,n}^{(0)} \cdot a_{0,n}^{(1)} = J^{\alpha_0+\alpha_1+\cdots+\alpha_n}$$
$$b_{1,n} = a_{0,n-1}^{(0)} \cdot a_{0,n}^{(1)} = J^{2\alpha_n^{(1)}+\alpha_0+\alpha_1+\cdots+\alpha_{n-1}}$$
$$b_{2,n} = a_{0,n}^{(0)} \cdot a_{0,n-1}^{(1)} = J^{\alpha_n^{(0)}+\alpha_0+\alpha_1+\cdots+\alpha_{n-1}}$$

The term $J=(j\pi h)=(1+j)/\sqrt{2}$ for the case of h=1/4. The (0) and (1) terms indicate the modulation index being used for the 2-ary constituents, that is, $h^{(0)}=h$ or $h^{(1)}=2h$. As in the 2-ary GMSK case, the 4-ary pseudo-symbol $b_{0,n}$ at any stage n also involves

prior demodulated symbols, and must resort to the same differential decode operation when demodulating the actual data symbol. Again, through trial and error, two spectrum preserving data precoding mappings have been found for the 4-ary GMSK signal with modulation index h=1/4.

$$\alpha_n = [d_n - d_{n-1} + 1]_{\mathrm{mod}\,8} \quad (\alpha_0 = d_0)$$

$$\alpha_n = [d_n - d_{n-1} + 3]_{\mathrm{mod}\,8} \quad (\alpha_0 = d_0)$$

These precoding mappings can be implemented in the data precoder 12 through the 4-ary precoder lookup table.

///

4-ary Precoder Lookup Table			
d_n	d_{n-1}	$\alpha_n=[d_n-d_{n-1}+1]_{mod8}$	$\alpha_n=[d_n-d_{n-1}+1]_{mod8}$
−3	−3	+1	+3
−3	−1	−1	+1
−3	+1	−3	−1
−3	+3	+3	−3
−1	−3	+3	−3
−1	−1	+1	+3
−1	+1	−1	+1
−1	+3	−3	−1
+1	−3	−3	−1
+1	−1	+3	−3
+1	+1	+1	+3
+1	+3	−1	+1
+3	−3	−1	+1
+3	−1	−3	−1
+3	+1	+3	−3
+3	+3	+1	+3

The first precoding mapping $\alpha_n=[d_n-d_{n-1}+1]_{mod8}$ results in an optimal pseudo symbol sequences produced by the Viterbi decoder 32.

$$b_{0,n} = J^n \cdot J^{d_n}$$
$$b_{1,n} = J^{n-1} \cdot J^{d_{n-1}+2\alpha_n^{(1)}}$$
$$b_{2,n} = J^{n-1} \cdot J^{d_{n-1}+\alpha_n^{(0)}}$$

The term J^n belongs to the set $\{\pm 1, \pm j, (\pm 1 \pm j)/\sqrt{2}\}$, and both $\alpha_n^{(0)}$ and $\alpha_n^{(1)}$ are deterministic functions of d_n and d_{n-1}. Similarly, the second precoding mapping $\alpha_n = [d_n - d_{n-1} + 3]_{mod8}$ results in an optimal pseudo-symbol sequence produced by the Viterbi decoder 32.

$$b_{0,n} = J^{3n} \cdot J^{d_n}$$
$$b_{1,n} = J^{3n-3} \cdot J^{d_{n-1} + 2\alpha_n^{(1)}}$$
$$b_{2,n} = J^{3n-3} \cdot J^{d_{n-1} + \alpha_n^{(0)}}$$

In both cases, with the decoding state defined as $S_n = (d_n)$, a 4^1-state 4^2-branch Viterbi algorithm is sufficient for demodulating the source symbols $\{d_n\}$ when three 4-ary matched-filters are used in the filter bank 28.

Figure 2 quantified the performance improvement achieved through the data precoding for both the 2-ary and 4-ary GMSK signals with BT=1/3. Simulation data show that, depending on the channel bit-error-rate of interest, a GMSK modem employing data precoding will render a 0.5 dB to 2.5 dB signal-to-noise ratio (SNR) enhancement over the same modem that employs no data precoding.

The function of the precoder 12 in the GMSK transmitter 10 is to precondition the symbol sequence α_k as an effective reverse function of differential encoding that intrinsically results from the GMSK modulation process. The precoding produces absolute phase demodulation achieved within the GMSK receiver 20. This absolute phase demodulation eliminates the need for differential decoding of

matched filters 28 while providing an improvement in signal detection performance. The preferred precoding algorithms are specific to M-ary CPM signals.

The present invention is directed to the precoding of a data sequence into an encoded sequence of transmitted symbols, to avoid differential decoding and for improving the BER using Laurent filtering. In the preferred form, a precoder is applied to 2-ary and 4-ary symbol sets used in a GMSK transmitter having a Gaussian filter defines by respective BT products and frequency modulator modulation indices. The preferred GMSK receivers included matched filters 28, sampling 30, and Viterbi decoding 32. The general form of the invention is a precoding method applicable to any M-ary symbol set, BT product, modulation index, bank of match filters, and Viterbi decoding algorithms. Those skilled in the art can make enhancements, improvements and modifications to the invention, and these enhancements, improvements and modifications may nonetheless fall within the spirit and scope of the following claims.

///

What is claimed is:

1. A method for communicating a data stream, the method comprising the steps of,

generating a sequence of data symbols from the data stream,

precoding the sequence of data symbols into a sequence of precoded data symbols,

modulating the sequence of precoded data symbols into a continuous phase modulated signal,

transmitting the continuous phase modulated signal,

receiving the continuous phase modulated signal,

demodulating the continuous phase modulated signal into a received baseband signal, and

filtering the received baseband signal into a sequence of filtered signals having absolute phase for indicating the sequence of data symbols.

2. The method of claim 1 further comprising the steps of ,

sampling the sequence of filtered signals into a sequence of sampled signals, and

decoding the sequence of sampled signals into an estimated data stream.

///

3. The method of claim 1 wherein,

the generating step comprises the steps of receiving the data stream of data bits, formatting the data stream into the sequence of formatted data pulses as a sequence data symbols within an M-ary symbol set,

the modulating step comprises the steps of Gaussian filtering and frequency modulating for generating the continuous phase modulated signal, the Gaussian filter step filters the precoded sequence of data symbols into pulse responses continuously accumulated over a finite memory time as a filter response, the Gaussian filtering step is defined by a bandwidth time product inversely defining the finite memory time, the frequency modulating step frequency modulates a carrier reference by the filter response by a modulation index for converting the filter response into the continuous phase modulated signal,

the demodulating step is carrier demodulating step for demodulating the continuous phase modulated signal using a local carrier into the baseband signal, the carrier demodulating step further removes a carrier phase offset between the local carrier and the received continuous phase modulated signal, and

the filtering step is a matched filtering step for matched filtering of the received baseband signal into the filtered signal, the matched filtering is matched by pulse amplitude modulation representation to the Gaussian filtering step, the filtered signal has an absolute phase at a periodic sampling time for indicating the sequence of data symbols.

4. The method of claim 3 wherein the modulating step, the modulation index is equal to a fraction selected from a group consisting of 1/M and 1-1/M for the M-ary symbol set.

5. A method for communicating data stream, the method comprising the steps of,

generating a sequence data symbols from the data stream by formatting the data stream into the sequence of formatted data pulses as a sequence data symbols within an 2-ary symbol set,

precoding the sequence of data symbols into a sequence of precoded data symbols,

Gaussian filtering the precoded sequence of data symbols into pulse responses continuously accumulated over a finite memory time as a filter response, the Gaussian filtering is defined by a bandwidth time product inversely defining the finite memory time,

frequency modulating a carrier reference by the filter response by a modulation index for converting the filter response into the continuous phase modulated signal,

demodulating the continuous phase modulated signal by a local carrier and by a carrier phase offset into a received baseband signal, and

matched filtering the received baseband signal into a filtered signal, the matched filtering is matched by pulse amplitude modulation representation to the Gaussian filtering, the filtered signal has an absolute phase at a periodic sampling time for indicating the sequence of symbols.

6. The method of claim 5, wherein,

the sequence of data symbols has a data symbol d_n at a current symbol time n and has a data symbol d_{n-1} at an immediate previous symbol time n-1 for precoding the data sequence into the sequence precoded data symbols having a precoded data symbol α_n at the current symbol time, the precoding step is defined by $\alpha_n = [\ d_n - d_{n-1} + 1\ ]_{mod4}$.

7. The method of claim 5, wherein,

the sequence of data symbols has a data symbol d_n at a current symbol time n and has a data symbol d_{n-1} at an immediate previous symbol time n-1 for precoding the data sequence into the sequence of precoded data symbols having a precoded data symbol α_n at the current symbol time for even symbol times and for odd symbol times, the precoding step is defined by $\alpha_n = [\ d_n - d_{n-1} + 1\ ]_{mod4}$ for even symbol times and $\alpha_n = -[\ d_n - d_{n-1} + 1\ ]_{mod4}$ for odd symbol times.

8. The method of claim 5 wherein the modulation index is 1/2.

9. The method of claim 5 wherein the bandwidth time product is 1/3.

10. The method of claim 5 wherein the filtering step is a matched filtering step for applying a principal Laurent function to the baseband signal so that the filtered signal comprises a principal Laurent component.

11. A method for communicating data stream, the method comprising the steps of,

generating a sequence data symbols from the data stream by formatting the data stream into the sequence of formatted data pulses as a sequence data symbols within an 4-ary symbol set,

precoding the sequence of data symbols into a sequence of precoded data symbols,

Gaussian filtering the precoded sequence of data symbols into pulse responses continuously accumulated over a finite memory time as a filter response, the Gaussian filtering is defined by a bandwidth time product inversely defining the finite memory time,

frequency modulating a carrier reference by the filter response by a modulation index for converting the filter response into the continuous phase modulated signal,

demodulating the continuous phase modulated signal by a local carrier and by a carrier phase offset into a received baseband signal, and

matched filtering the received baseband signal into a filtered signal, the matched filtering is matched by pulse amplitude modulation representation to the Gaussian filtering, the filtered signal has an absolute phase at a periodic sampling time for indicating the sequence of symbols.

12. The method of claim 11, wherein,

the sequence of data symbols has a data symbol d_n at a current symbol time n and has a data symbol d_{n-1} at an immediate previous symbol time n-1 for precoding the data sequence into the sequence precoded data symbols having a precoded data symbol α_n at the

current symbol time, the precoding step is defined by $\alpha_n = [\ d_n - d_{n-1} + 1\ ]_{mod8}$.

13. The method of claim 12 wherein the precoded data symbol α_n is defined by the 4-ary symbol set of +1, -1, +3 and -3.

14. The method of claim 12 wherein the modulation index is 1/4.

15. The method of claim 11, wherein,

the sequence of data symbols has a data symbol d_n at a current symbol time n and has a data symbol d_{n-1} at an immediate previous symbol time n-1 for precoding the data sequence into the sequence precoded data symbols having a precoded data symbol α_n at the current symbol time, the precoding step is defined by $\alpha_n = [\ d_n - d_{n-1} + 3\ ]_{mod8}$.

16. The method of claim 15 wherein the precoded data symbol α_n is defined by the 4-ary symbol set of +1, -1, +3 and -3.

17. The method of claim 15 wherein the modulation index is 1/4.

18. The method of claim 11 wherein 10 wherein the filtering step is a matched filtering step for applying a principal Laurent function, a third Laurent function and a twelfth Laurent function to the baseband signal so that the filtered signal comprises a principal Laurent component, a third Laurent component and a twelfth Laurent component.

19. The method of claim 11 wherein the modulation index is 3/4.

20. The method of claim 11 wherein the bandwidth time product is 1/3.

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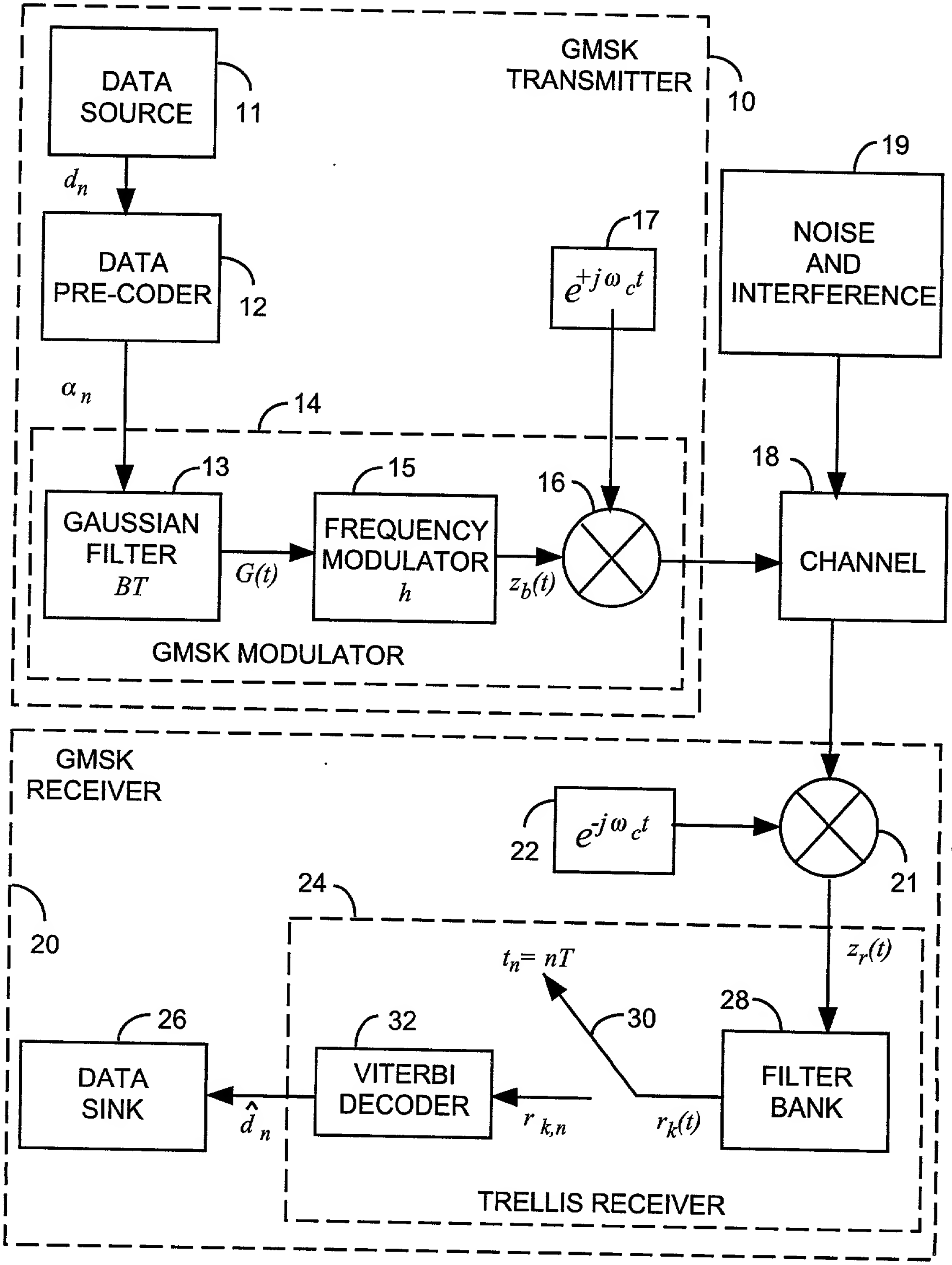
Abstract of the Disclosure

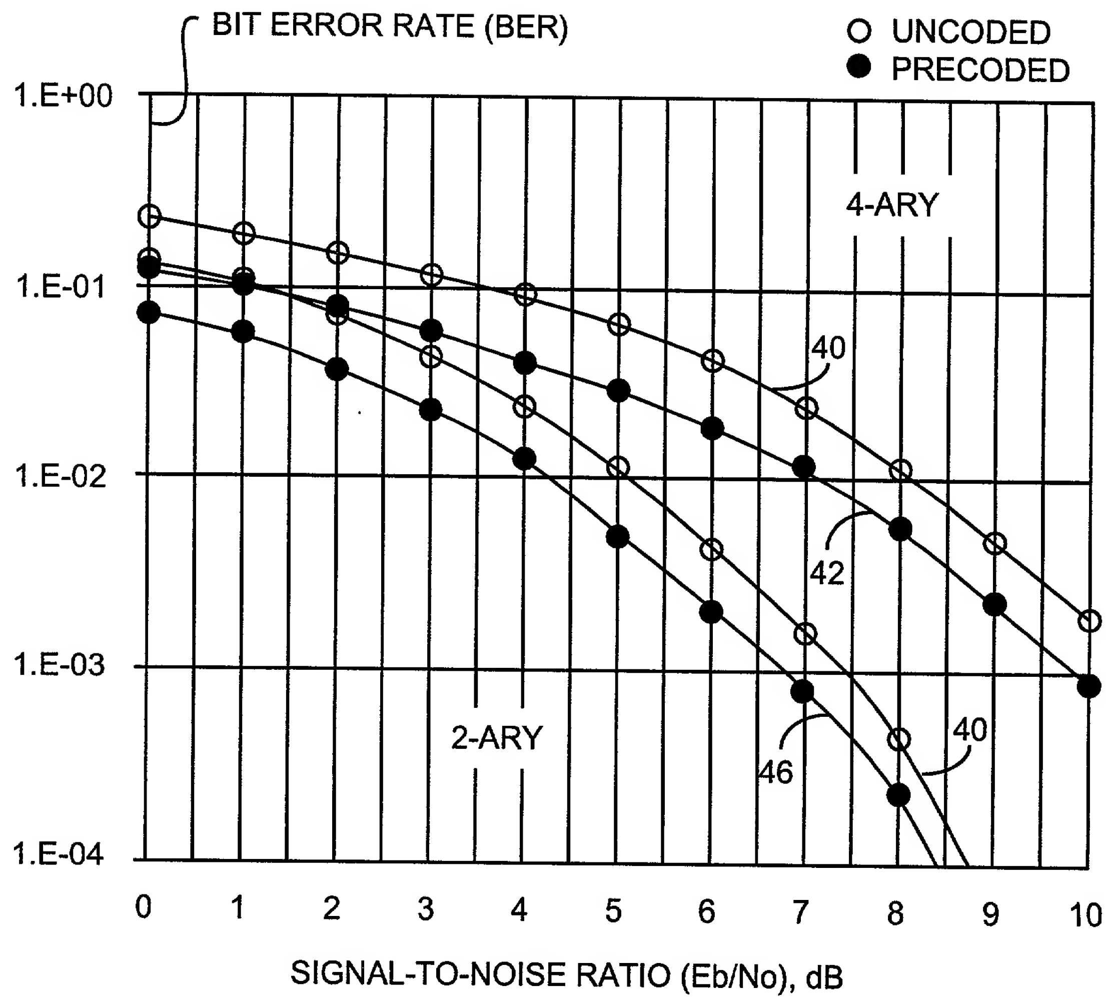
A premodulation precoding method precodes a data sequence in a Gaussian minimum shift keying (GMSK) modulator to improve the bit error rate performance of a coherent Viterbi receivers generating estimates of the communicated data sequence without the use of differential decoding while preserving the spectrum of 2-ary and 4-ary GMSK signals over a wide range of bandwidth time products.

///



PRECODED COHERENT GMSK COMMUNICATION SYSTEM

FIG. 1



BER PERFORMANCE OF PRE-CODED
AND UN-CODED GMSK WITH BT = 1/3

FIG. 2

PATENT

Attorney's Docket No. D-349

COMBINED DECLARATION AND POWER OF ATTORNEY

As a below named inventor, I hereby declare that:

TYPE OF DECLARATION

This declaration is of the following type:

/X/ original

INVENTORSHIP IDENTIFICATION

My residence, post office address and citizenship are as stated below next to my name, I believe I am the original, first and sole inventor (if only one name is listed below) or an original, first and joint inventor (if plural names are listed below) of the subject matter which is claimed and for which a patent is sought on the invention entitled:

TITLE OF INVENTION

GAUSSIAN MINIMUM SHIFT KEYING (GMSK) PRECODING COMMUNICATION METHOD

SPECIFICATION IDENTIFICATION

The specification of which is attached hereto.

ACKNOWLEDGEMENT OF REVIEW OF PAPERS AND DUTY OF CANDOR

I hereby state that I have reviewed and understand the contents of the above identified specification, including the claims, as amended by any amendment referred to above.

I acknowledge the duty to disclose information which is material to the examination of this application in accordance with Title 37, Code of Federal Regulations section 1.56(a).

/X/ In compliance with this duty there is attached an information disclosure statement. 37 CFR 1.97.

(Rel.33-4/87 Pub.605) FORM 1-1

POWER OF ATTORNEY

As a named inventor, I hereby appoint the following attorney(s) and/or agents(s) to prosecute this application and transact all business in the Patent and Trademark Office connected therewith:

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DECLARATION

I hereby declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both under Section 1001 of Title 18 of the United States Code and that such willful false statements may jeopardize the validity of the application or any patent issued theron.

SIGNATURE(S)

Full name of sole or first inventor: Gee L. Lui
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Full name of third joint inventor, if any: ____
Inventor's signature: ____
Date: ____ Country of Citizenship: ____
Residence: ____
Post Office Address: ____

X This Declaration ends with this page-- page 2 of 2)

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Full name of third joint inventor, if any: ________
Inventor's signature: ________
Date: ________ Country of Citizenship: ________
Residence: ________
Post Office Address: ________

X This Declaration ends with this page-- page 2 of 2)